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Fast Probing Considerations For On-Machine Inspection of Parts

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Abstract

A calibration procedure for on-machine probing is developed. This is necessary if the machine is used as a coordinate measuring machine to measure the absolute part dimensions. This is most crucial in turning machines where the turret is unable to go below the centerline of the part. However, in measurements on turning centers and machining centers where a differential measurement can be achieved on a feature, calibration is not as crucial. On-machine-probing variables, such as the feed rate at which probing occurs, have a proportional relationship to effective errors in the timing of the probe triggering system. Experiments were performed to verify and model machine feed rate during probing with resulting systematic measurement error.

1.0 Introduction

The Closed-Loop Machining Systems Program of the Manufacturing Engineering Laboratory at the National Institute of Standards and Technology has the goal of developing the basic tools related to infrastructure (data, information/knowledge repositories, models, and algorithms) needed to monitor and control machining processes for improved accuracy of machined parts, and to reduce lead-time to allow production of quality products in a cost-effective manner.

One method of improving the accuracy of parts is to use process-intermittent gauging [1-5], which probes the workpiece while it is fixtured on the machine, but machining is not taking place simultaneously. In process-intermittent gauging, a touch-trigger probe is used in a rapid fashion between the semi-finish and finish cuts of a part. The probing data may be used to adjust the depth of cut or modify more complicated aspects of the tool path to correct for errors that may be present in the process from sources such as tool wear and tool or part deflections.

Fast part probing using a touch-trigger probe, with about one probe trip per second, is desired to minimize the time consumed by the measurement. If on-machine probing was included in production, fast probing would decrease manufacturing time and therefore increase productivity. At the time the probing system was installed, typical probing cycles were on the order of 120 mm/min to 200 mm/min (5 to 8) ipm [7-8] and were slow in transferring axes coordinates for the probed points to external computers, usually through RS-232 interfaces for distributed numerical control (DNC) [2].

To implement fast probing, a smart, machine-controller interface called the Real-Time Error Corrector (RTEC) is used [1-6]. The RTEC is inserted between the position feedback devices of the machine tool (i.e., linear scales) and the machine tool controller. Signals in the form of interrupts are sent from the probing system (indicating contact with a surface) to the RTEC to latch the machine axes' positions. With the use of fast probing, the feed rates well exceeded those recommended by probe vendors. However, as stated in [2], for precision probing, the effect of inherent delays within the system, the probe radius, and the effect of probe-trip force and pretravel must all be carefully calibrated at each velocity and direction of approach to be used. The need and plan for a calibration procedure for effective probe tip radius for on-machine part inspections is discussed in this report.

2.0 Test Procedure and Results

Due to observed inconsistencies between data obtained by process-intermittent (PI), on-machine, probing and the data obtained by post-process Coordinate Measuring Machine (CMM) probing on an experimental part (similar to the part shown in Figure 1), experiments were performed to investigate the source(s) of error. The objective was to identify element(s) in the probing system that caused the measurement discrepancies. The elements and corresponding possible errors in the on-machine, part-inspection system are: (1) the probe body, possible electronic or mechanical malfunction, (2) the probe communication system (transmitter/receiver), possible delays in transmitting and/or receiving data once the probe touches the workpiece, and (3) possible delays unaccounted for in collection and/or transmission of data collected by the RTEC.

The original, noted discrepancy is shown in Figure 2, which is a comparison of the approximate radius of 1/4 of a circular feature profile, probed on the CMM and on the PI system. The associated uncertainties of the measurements on the CMM and the PI system are approximately 2 μm each. The estimated radius from the measured points for each system is found by using a nonlinear least squares algorithm which includes 17 points within the 1/4 circular feature profile. The uncertainties of the estimates of the radius for the 1/4 circular feature profile were approximately 3.5 μm for each of the CMM and the PI systems. Comparing the CMM- and the PI-measured data, the form error appears to be very similar, but an unexpected offset exists of approximately 0.290 mm (0.0114 in). For the calibration study outlined in this report, the initial experiments were designed to determine if a pretravel error was present that would be comparable to the offset of 0.290 mm (0.0114 in), in Figure 2. Pretravel errors occur when there is a delay between the time the probe touches the part and the time the machine position is recorded.

The process intermittent measurements are performed using a Renishaw LTO2S Probing System[1], which is mounted on a turning center. The LTO2S infra red (IR) transmission system includes an optical module probe (OMP), which provides communication between the turret-mounted probe and an optical receiver mounted in the field of view of the LTO2S OMP. An MI 14 Interface Unit converts the optical probe signals into a readable signal for the RTEC. Figure 1 shows a typical configuration of the touch trigger probe measuring a test part mounted on the turning center. The probe stylus used, and shown in Figure 1, has a 2.5 mm (0.0985 in) radius ruby ball.

[1] Commercial equipment, instruments, or materials are identified in this report in order to specify adequately certain procedures. In no case, does such identification imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the material or equipment identified is necessarily the best available for the purpose.

First, a 0.7500 in diameter reference sphere, which is used in probe calibration for the CMM, was measured using the PI probing system on the turning center. A photograph of the experimental setup is shown in Figure 3. Due to a limitation of 2 degrees of freedom of machine movement on the lathe, a full 49-point probe calibration test outlined in [9] could not be performed. Instead, a total of 80 points were measured along the circular profile of the sphere in the vertical plane. The measured portion of the profile corresponds to 100° of a full circle. A circle was then fitted to the data using a least-squares nonlinear optimization algorithm. Ideally, the radius of the fitted circle should be the addition of the radius of the reference sphere, 9.53 mm (0.375 in), and the radius of the stylus tip, 2.5 mm (0.0985 in), with a resulting measured radius of 12.03 mm (0.4735 in). However, the radius fitted to the measured data was 11.75 mm (0.4626 in), with a discrepancy from the ideal value of 0.2759 mm (0.0109 in), which is consistent with the 0.290 mm offset illustrated in Figure 2. The standard uncertainty of the estimated radius using the 80 points about the reference sphere is approximately 2 µm.

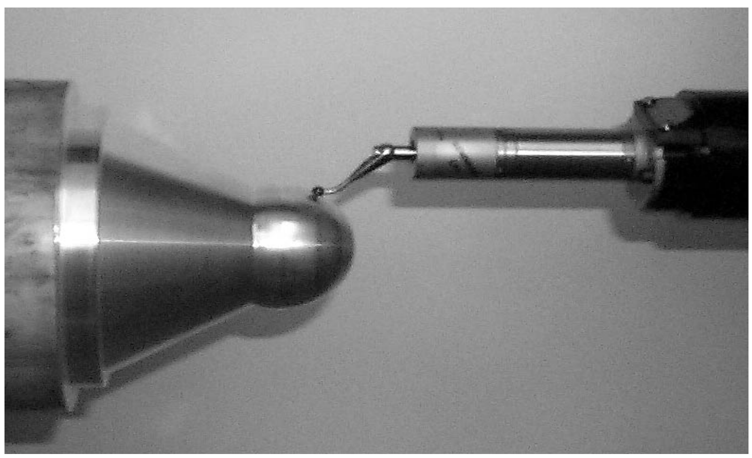

Figure 1. Fast Probing on a part, which checked machining errors on a Turning Center.

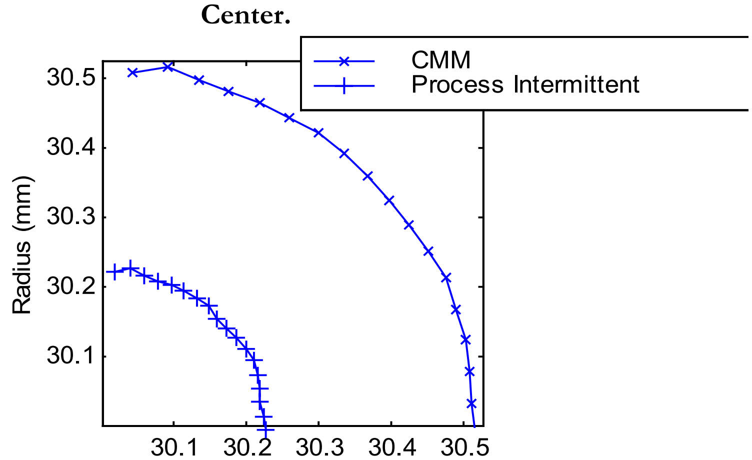

Figure 2. Comparison between fitted 1/4 circle data taken on the CMM and on the Turning Center Process Intermittent Probe System.

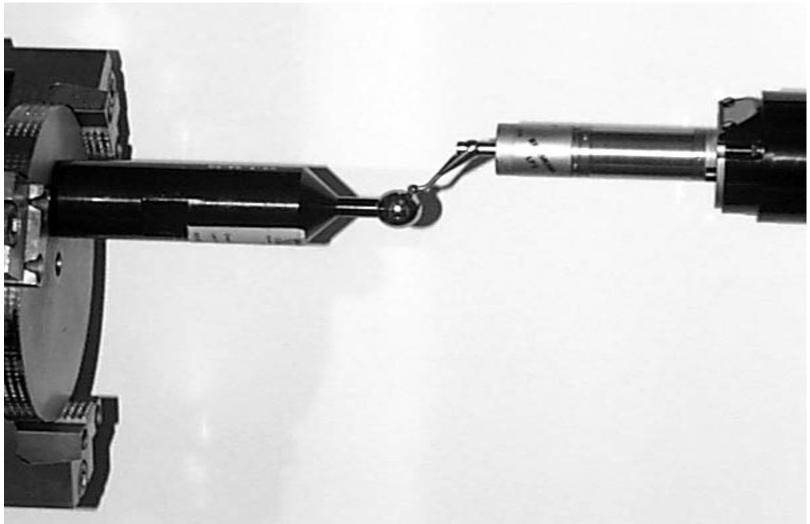

Figure 3. Fast probing of 0.75 in sphere.

Another experiment was performed using a 2 inch gage block. The gage block was positioned parallel to the machine's vertical axis. The probing was made in the vertical direction, where the upper and lower surfaces of the gage block were probed as shown in Figures 4 and 5 respectively. Two items were varied during these experiments: (1) feed rate, and (2) angular orientation of the probe body. The angular orientation of the probe body was varied to test the effect of angular orientation of the probe body on measurement error. If certain angular orientations of the probe body were more susceptible to errors than others, then an optimization of angular orientation would be performed to minimize measurement error. The feed rates used in experimentation were chosen to note the effects of feed rate on measurement error due to trigger delay. At or below the feed rates recommended for use by the manufacturer, 120 mm/min to 200 mm/min (5 to 8) ipm, the trigger delay was expected to have a small effect on measurement error. However, the main interest was to find the effect at 2540 mm/min (100 ipm), the feed rate that is used in fast probing on our machine. The feed rates chosen for the experiments were 25.4 mm/min (1 ipm), 50.8 mm/min (2 ipm), 127 mm/min (5 ipm), 254 mm/min (10 ipm), 508 mm/min (20 ipm), 1270 mm/min (50 ipm) and 2540 mm/min (100 ipm). The chosen probe body angles were 0°, 7°, ± 10°, ± 20°. The probe body angles were measured with respect to the position of installation at the start of this series of experiments. At least 50 points were taken for each experiment (feed rate and angular orientation combination) to determine the repeatability of the measurement. The range of variation of the probed points is within 3 μm (118 μin) as read by the RTEC.

The RTEC facilitates fast part probing with touch-trigger probes by latching the axes' positions in response to a measuring probe release (or trip) and reports the positions to a PC. The probing system operates as follows. Once the probe tip touches a surface, a signal is generated to signal the RTEC to latch the axes' positions. The result of the experiment used to measure the timing of the of the probing system once the probe tip touches a surface is reported later in this report. The position data is produced independent of the machine tool controller (MTC). The MTC executes a part program, which moves the probe towards the part surface until it passes the ideal surface by approximately 2.5 mm, at a feed rate of 2540 mm/min (100 in/min). On the turning center, the linear scales produce encoder-type, position-feedback signals, which are continuously decoded and counted in the RTEC. During probing, the probe-trip signal, which indicates the contact of the probe tip with the target surface, "holds" the trip position at the decoder output until the microcomputer can read the position. The decoder is designed to continue to count the encoder signals to track the

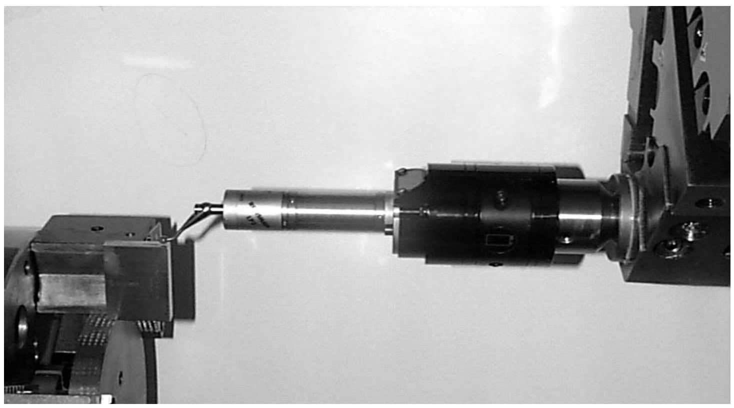

Figure 4. Probing setup to measure upper end of the 2 inch gauge block as mounted on the Turning Center.

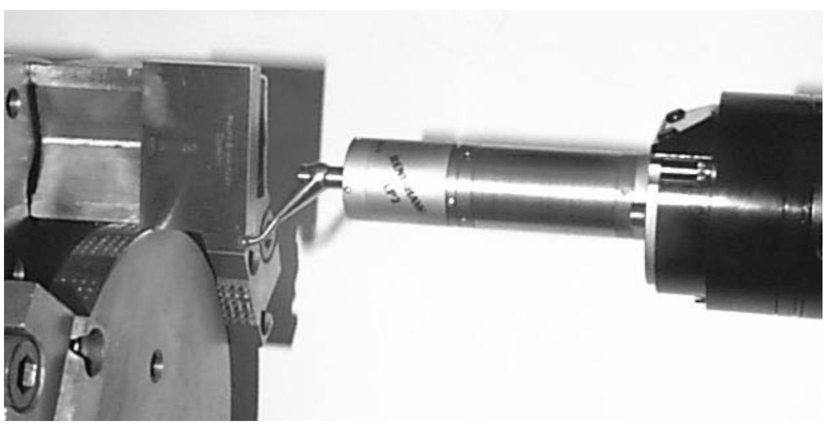

Figure 5. Probing setup to measure lower end of the 2 inch gauge block as mounted on the Turning Center.

machine position. At 2540 mm/min (100 in/min), the machine moves one micrometer (the position resolution of the turning center) in 24 microseconds. For optimum repeatability in part inspection, the probe must trip during the constant velocity (programmed feed rate) portion of each point-to-point move so that with the effect of any repeatable delays in the system, a constant distance offset will result. Usually, machines accelerate at approximately a constant rate until the programmed velocity is reached and maintain constant velocity until a specific distance from the programmed end point is reached, then decelerate to stop at the programmed end point. Figure 6 illustrates a velocity profile of the machine's programmed feed rate. The acceleration and deceleration times are a function of the specific axis drive system. The starting and ending points of the programmed probe motion must be chosen to ensure tripping during the constant velocity portion of the move. At any given time, the actual machine position lags the programmed position due to "following error", which is a function of servo-loop gain For the turning center used in these experiments, the "following error" is about 1.78 mm (70 milli-in) at 2540 mm/min (100 in/min) feed rate. To allow time for acceleration to 2540 mm/min (100 in/min) the probe should be programmed to move from a position approximately 5.1 mm (0.2 in) away from the workpiece to a position 2.5 mm (0.1 in) beyond the part edge to allow time to decelerate (which must be within the probe overtravel limit). This results in 3 mm (0.12 in) of constant velocity travel. A maximum error or target window in the actual position of the surface (trip point) of $\pm$ 1 mm ($\pm$ 0.04 in) could be tolerated. Since the probe trip signal holds the true position count from the feed-back device, the servo lag does not cause a dimensional error. [2,4]

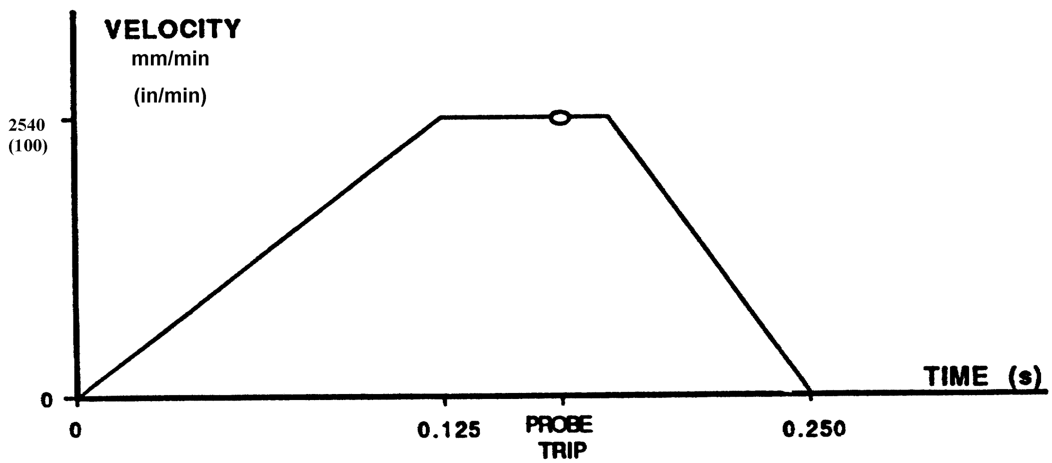

Figure 6. Velocity Profile of the Turning Center's Programmed Feed Rate.

An experiment was performed, using manual triggering to measure the timing of the generation of the probe output signal in relation to the time of the probe trip. As mentioned previously, once the probe tip touches a surface, a signal is generated within the probe assembly, which triggers the RTEC to latch the machine axes' positions.

Since there is no convenient way to monitor signals generated internal to the probe while doing actual on-machine probing, the probe body was removed from the IR transmitter portion of the assembly. A connection was then made by actually holding probes on the switch closure connecting rings and pins to measure the voltage across the switch contacts. This voltage was used to trigger the oscilloscope and was also recorded on one channel of the dual channel oscilloscope (see the upper trace of Figure 7). The second input to the oscilloscope was connected from the output signal of the probing system, which triggers the RTEC machine position capture circuits (see the lower trace of Figure 7). Manual triggering the probing system permits the measurement of the time delay between the probe switch closure and the probing system output signal that triggers the RTEC. The probing system was operated manually to approximate rates currently used for fast part probing.

As can be seen in the upper trace of Figure 7, the input circuit also records the internal characteristics of the probing system as measured at the connecting rings and pins, namely the charge and trigger levels. Figure 7 is a graphical representation of what was measured with an oscilloscope. The operation of the probing system can be explained as follows. 'Probe Touch' is the section in the waveform as measured across the slip rings in the probe when the touch switch is closed. A jump occurs because of the resistor-capacitor charge circuit. The actual circuit within the probe is unknown, but the waveform suggests that there is a small resistance in series with a capacitor such that when the initial closure of the switch occurs, there exists a simple series resistive divider effect until the capacitor starts to charge. A measured step of approximately 300 mV occurs just prior to the start of the capacitor charge would suggest this type of circuit. This charge continues until the switch is opened, however, at the level marked 1.8 V, the step labeled 'Capture Machine Position' in the lower trace of Figure 7 changes state. This change of state is the point where the actual RTEC triggering occurs, resulting in the RTEC capture position input signal. It remains at that state until the probe switch is opened at the point labeled 'Switch Release' on the upper trace of Figure 7. At fast probing rates, the delay between the actual switch closure and the probing system output signal (the trigger signal to the RTEC capture circuit) was measured to be approximately 6 ms, with no significant variance.

This circuit response of the probing system suggests that a voltage level greater than the initial 300 mV jump was chosen to eliminate switch bounce and/or noise during probe switch closure. The delay is associated with the charge time constant of the RC network.

This hypothesis of probe operation is not verified by inspection of the internal circuit of the probing system, mainly because the construction of the probe prohibits dissection without destroying the probe assembly. In addition, the electronic schematic is not available for the probing system. This analysis of the operation is, however, consistent with the practice of good electronic design, given the voltage waveforms observed during the measurements.

The purpose of this experiment was not to characterize the probe circuit fully at all feed rates, or to characterize the timing of all of the components in the probing system. The only purpose was to verify that there was a delay between the time when the probe touches a surface and when the position is registered, which was measured to be approximately 6 ms. The authors of this report recommend that users perform calibrations with precision gage blocks or spheres at the feed rate(s) of interest. If the probing feed rate is 2540 mm/min (100 in/min), then a 6 ms time delay between the time the probe touches the surface of the part and the time the machine position is recorded yields a distance error in the measurement of 0.254 mm.

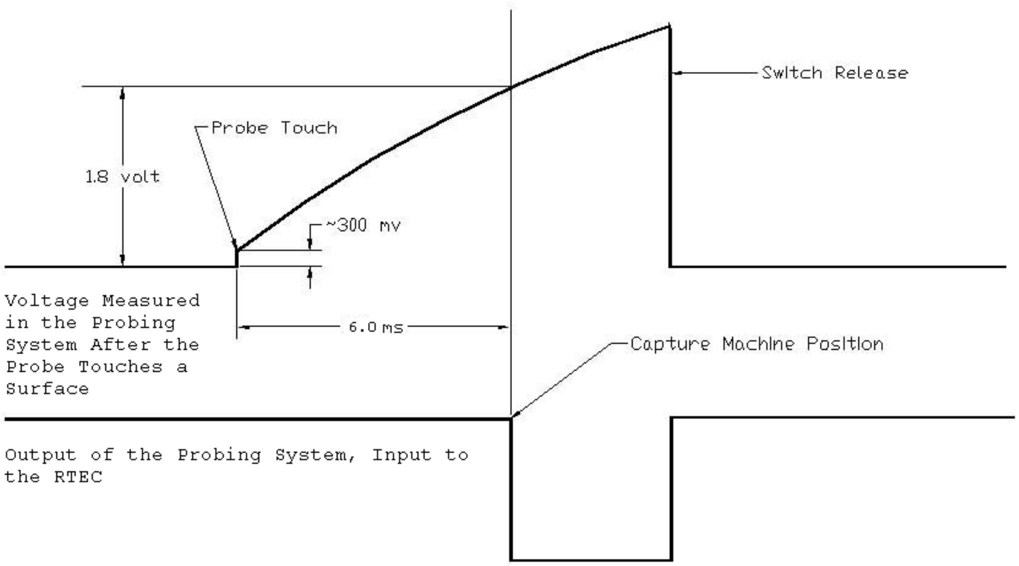

Figure 7. Graphical representation of the measurement of the time delay of the switch that captures position for the process-intermittent probing system.

For the gage block experiments, the movement of the lathe was programmed to move in rapid mode (e.g., G00) to the points at which the probe would be positioned to probe the part and then the feed rate was varied with the motion of touching the part with the probe (e.g., G01 F##). Therefore, the effects of backlash are constant with the variation of feed rates. The recorded machine position of the probe trip is located in the center of the stylus tip and therefore stylus tip radius should be subtracted from the measurements. The difference between measured and nominal of the size of the gage block and probe, Δ , was calculated with the following equation,

$$\Delta \; = mean(UP) - mean(LP) - (\; + 2 \times r) \;\; \mu\text{m} \qquad (1)$$

Where *UP* are the probed points (machine location) at the top of the gage block, *LP* are the probed points at the bottom of the gage block,   is 50.8 mm (2 in), the nominal dimension of the gage block and r is 2.5019 mm (0.0985 in), the nominal radius of the stylus tip.

A summary of the measured differences associated with each feed rate and angle of the probe body is given in Table 1. In most cases, the standard deviation of the probed points indicate that the repeatability of the probed points are within 1 µm as read by the RTEC.

Part of the necessary processing of data taken by probing a machined part is to remove the introduction of effects of probe radius. Since the data recorded from the probing system is at the location of the center of the ball at the tip of the probe stylus, the actual part size is calculated by the appropriate compensation of probe radius. Since the probing delays are repeatable for a given feed rate, then the errors may be noted and corrected as an effective size error of the probe stylus tip. A simple method of correction for time delay would be to use a proportionately smaller effective probe tip radius. For the gage block experimental data, since the measurement of the gage block involved measuring two ends of the block, the probe diameter error is calculated. The nominal probe diameter was subtracted from the effective probe diameter (the result from subtracting the size of the gage block from the probing measurements), which resulted in a probe diameter error. The probe diameter error as a function of feed rate was fit to the following equation of a line,

$$\Delta d = 10.07 - 0.2054 \times F \qquad (2)$$

where Δd is the probe diameter error (µm), and F is the feed rate (mm/min). A plot of the data collected for *effective probe diameter error* vs. *feed rate* is shown in Figure 8. As the feed rate increases, so does the error between the actual and effective diameter of the probe tip diameter. Since the plot as scaled does not highlight the differences in the probe body rotation, a comparison of results from various rotations of probe body with respect to the probe body position normally used (0 degrees) is shown in Figure 9. At a feed rate of 254 mm/min (10 ipm), the error associated with the comparison of probe rotation of 20 degrees and 0 degrees is highest (approximately 4.5 µm). A feed rate of 2540 mm/min (100 ipm) is normally used in the Process Intermittent probing, and therefore a compilation of measurements which compares effective probe diameter error vs. probe body rotation is made in Figure 10. The maximum error is about 3 µm as read by the RTEC, which is relatively small compared with the overall effective probe diameter error. Probe sensitivity to rotation angle is therefore considered not significant to include in the calibration procedure for the process-intermittent loop on the turning center system.

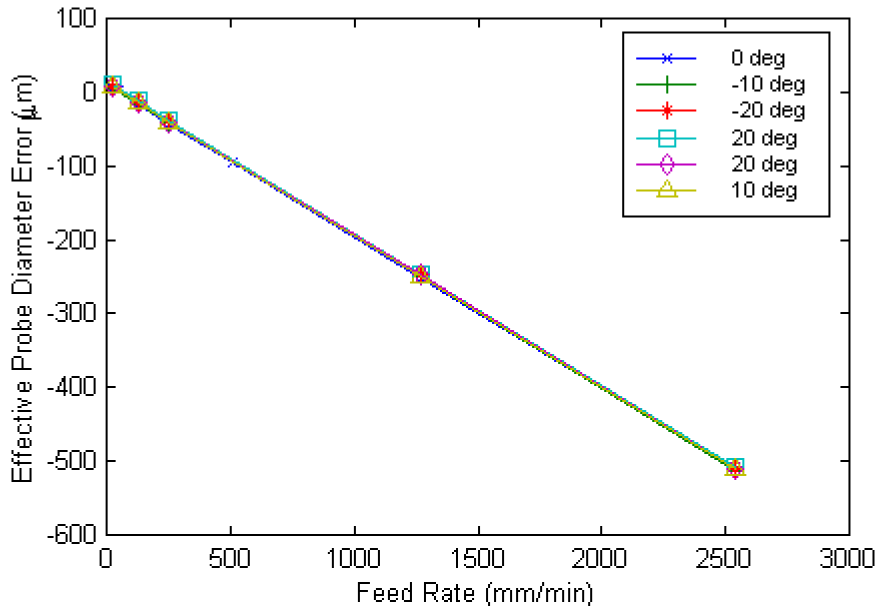

Figure 8. Effective Process Intermittent Probe Diameter Error vs. Machine Feed Rate.

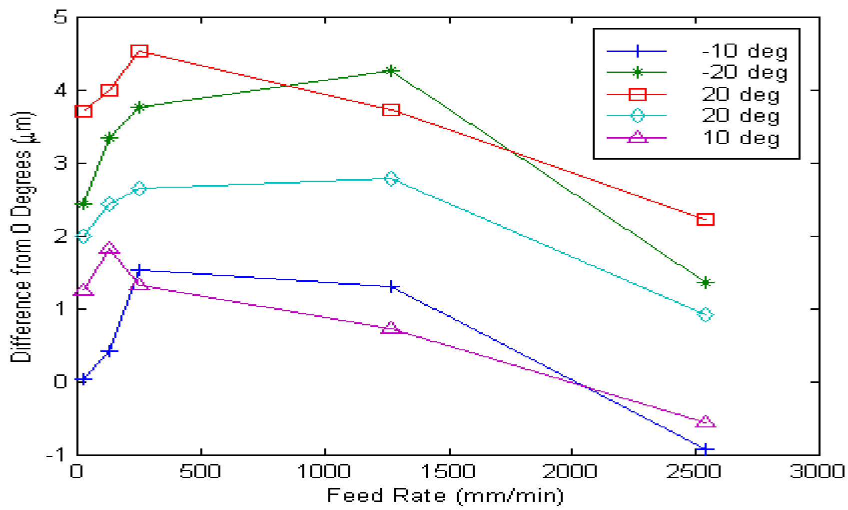

Figure 9. Comparison of Results from Various Rotations of Probe Body with Respect to the Probe Body Position Normally Used (0 degrees).

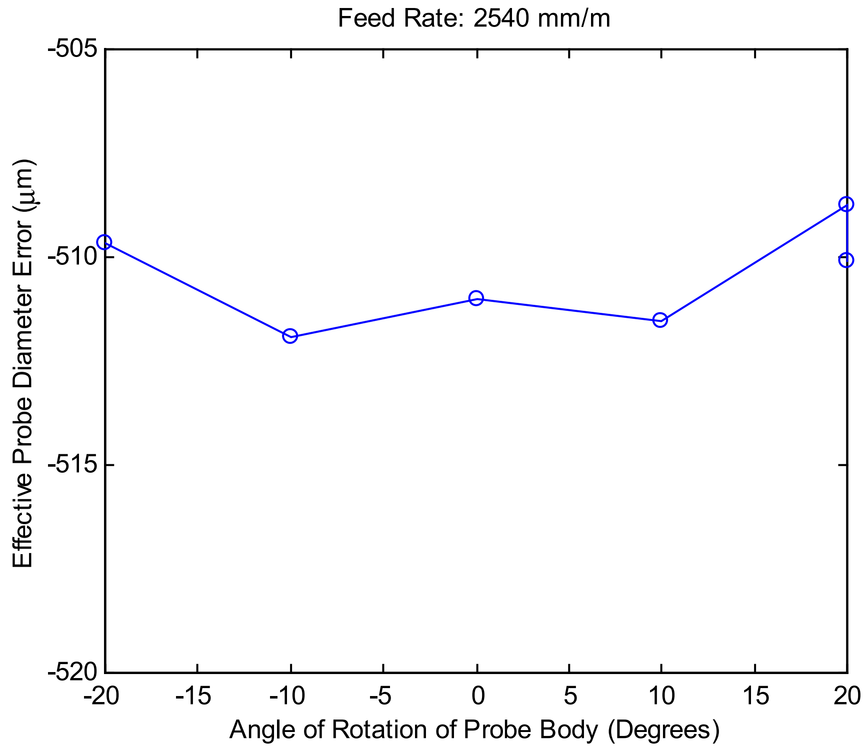

Figure 10. Display of Minimal Variation (2.5μm max error) Between Measurements at Various Angular Positions of Probe Body.

3.0 Summary

Experiments were performed for the measurement of variations in on-machine probing. The manufacturer-recommended feed rate for probing is 120-200 mm/min (5-8 ipm). Although the real-time error corrector made probing possible at feed rates of up to 2540 mm/min (100 ipm), due to the current design of the probing system which results in a time delay, a calibration for compensation needs to be performed for the feed rate of interest. At a feed rate of 2540 mm/min (100 ipm), a time delay of approximately 6 ms was measured between the time the probe hit the surface until the time the position of the machine was recorded. Since the probe measurement data requires compensation for the stylus probe tip radius, a simple method of correction for time delay would be to use a proportionately smaller effective tip radius. At 2540 mm/min (100 ipm), the correction for the probe radius is -254 μm (-0.010 in). Using this correction, it was possible to remove the inconsistencies between the CMM measurements and the on-machine measurements.

4.0 Acknowledgements

We thank Bruce R. Borchardt (PED) for consultation in CMM programming and operations, and for suggesting the possibility for pretravel errors in the process-intermittent measurements. We also thank Robert J. Gavin (APTD) for consulting with measurements for the RTEC/Probing system. We also thank Ken W. Yee (retired APTD) for discussions and guidance related to part probing.

5.0 References

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FEED RATE (mm/min)	ANGLE (DEGREES)	MEAN UPPER PROBE POINT (µm)	MEAN LOWER PROBE POINT (µm)	STANDARD DEVIATION OF THE UPPER PROBE POINT (µm)	STANDARD DEVIATION OF THE LOWER PROBE POINT (µm)	DIFFERENCE BETWEEN MEASURED AND NOMINAL GAUGE BLOCK AND PROBE SIZES (µm)
2540	0	-52437.26	-107730.06	0.63	0.55	-511.00
1270	0	-52307.58	-107860.00	0.54	0.35	-251.38
508	0	-52233.34	-107940.80	0.48	0.53	-96.34
254	0	-52206.22	-107966.65	0.57	0.59	-43.37
127	0	-52192.74	-107980.50	0.63	0.58	-16.04
50.8	0	-52179.98	-107985.66	0.38	0.52	1.88
25.4	0	-52180.20	-107989.72	0.71	0.61	5.72
2540	7	-52737.84	-108037.32	2.43	2.21	-504.32
1270	7	-52612.00	-108165.37	0.45	0.61	-250.43
254	7	-52506.48	-108268.48	0.59	0.59	-41.80
127	7	-52491.56	-108280.12	0.51	0.44	-15.24
25.4	7	-52480.24	-108290.32	0.52	0.48	6.28
2540	-10	-52572.00	-107863.88	0.76	0.53	-511.92
1270	-10	-52443.24	-107996.96	0.44	0.54	-250.08
254	-10	-52338.04	-108100.00	0.54	0.00	-41.84
127	-10	-52325.15	-108113.35	0.54	0.49	-15.61
25.4	-10	-52314.24	-108123.80	0.44	0.50	5.76
2540	-20	-52523.92	-107818.08	0.76	0.40	-509.64
1270	-20	-52394.56	-107951.24	0.71	0.60	-247.12
254	-20	-52289.35	-108053.54	0.49	0.58	-39.61
127	-20	-52276.11	-108067.21	0.50	0.42	-12.69
25.4	-20	-52266.32	-108078.28	0.56	0.46	8.16
2540	20	-52356.80	-107651.84	0.87	0.75	-508.76
1270	20	-52225.00	-107781.16	0.76	0.62	-247.64
254	20	-52122.20	-107887.16	0.41	0.37	-38.84
127	20	-52109.32	-107901.08	0.48	0.49	-12.04
25.4	20	-52098.52	-107911.76	0.51	0.44	9.44
2540	20	-52365.68	-107659.40	0.80	0.50	-510.08
1270	20	-52233.76	-107788.96	0.60	0.61	-248.60
254	20	-52130.92	-107894.00	0.40	0.41	-40.72
127	20	-52116.76	-107906.96	0.66	0.45	-13.60
25.4	20	-52104.00	-107915.52	1.04	0.87	7.72
2540	10	-52411.16	-107703.40	0.75	0.58	-511.56
1270	10	-52280.52	-107833.68	0.77	0.48	-250.64
254	10	-52175.57	-107937.32	0.50	0.48	-42.05
127	10	-52161.52	-107951.11	0.51	0.58	-14.21
25.4	10	-52149.78	-107960.56	0.70	0.51	6.98

Table 1. Summary of Results from Probing a 2-inch Gauge Block at Various Feed Rates.

Appendix A. Numerical Control Programs

A1. NC Program to Measure Reference Sphere

The NC program listing here was used to measure the 0.75 inch diameter test sphere. This program was generated by using Matlab to calculate the touch and clearance points around the sphere, then a C program was used to generate the NC program directly from the calculated points. The C program is listed in Appendix B.

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N0010 (ID,PROG,SPHERE,SPHERE TEST PROBING)
N0020 ! Fri Mar 11, 1999
N0030 ! Tool 5:  Touch-trigger probe w/ext. in 7.1" boring bar holder.
N0040 !   Length: Z=-10.7015  X=-7.9315    Offset 5: Z=-0.1000  X=0.0200
N0050 ! Touch face of part, then MDI W2.2985 for PROBING START
N0060 ! P43 = PROBING START: Machine Z coordinate to which
N0070 !   probe moves from the "standard" initial machine coordinates
N0080 !   [X0, Z10].
N0090 ! Probe tip diameter = 0.197"
N0100 ! Feedrate = 100 (inches per minute)
N0110 ! Touch face at Z-1.8, part zero is on dome surface.
N0120 ! Program probes 81 pts on SPHERE over 200 degrees
N0130 G70              ! INCH MODE
N0140 T0500                    ! INDEX TURRET TO PROBE
N0150 G94 T00          ! INCHES/MIN, CLEAR TOOL
N0160 G00 Z(P43)       ! RAPID TO PROBING START
N0170 G92 X30.4 Z13.0   ! PRESET REF COORDS
N0180 M14              ! TURN ON PROBE
N0190 M15              !
N0200 G01 X0.4 Z2.0 F100 T0505  ! CLEAR TEST SPHERE
N0210 G01 X1.17047 Z-0.49224
N0215 G01 X1.76136 Z-0.44014
N0225 G01 X1.17047 Z-0.49224
N0240 G04 X3.0
N0260 G01 X1.16151 Z-0.46313
N0265 G01 X1.75638 Z-0.42397
N0275 G01 X1.16151 Z-0.46313
N0290 G04 X3.0
N0310 G01 X1.15510 Z-0.43385
N0315 G01 X1.75281 Z-0.40771
N0325 G01 X1.15510 Z-0.43385
N0340 G04 X3.0
N0360 G01 X1.15125 Z-0.40446
N0365 G01 X1.75067 Z-0.39138
N0375 G01 X1.15125 Z-0.40446
N0390 G04 X3.0
N0410 G01 X1.14996 Z-0.37502
N0415 G01 X1.74996 Z-0.37502
N0425 G01 X1.14996 Z-0.37502
N0440 G04 X3.0
N0460 G01 X1.15125 Z-0.34558
N0465 G01 X1.75067 Z-0.35866
```

```
N0475 G01 X1.15125 Z-0.34558
N0490 G04 X3.0
N0510 G01 X1.15510 Z-0.31619
N0515 G01 X1.75281 Z-0.34233
N0525 G01 X1.15510 Z-0.31619
N0540 G04 X3.0
N0560 G01 X1.16151 Z-0.28691
N0565 G01 X1.75638 Z-0.32607
N0575 G01 X1.16151 Z-0.28691
N0590 G04 X3.0
N0610 G01 X1.17047 Z-0.25780
N0615 G01 X1.76136 Z-0.30990
N0625 G01 X1.17047 Z-0.25780
N0640 G04 X3.0
N0660 G01 X1.18196 Z-0.22892
N0665 G01 X1.76774 Z-0.29385
N0675 G01 X1.18196 Z-0.22892
N0690 G04 X3.0
N0710 G01 X1.19596 Z-0.20031
N0715 G01 X1.77552 Z-0.27796
N0725 G01 X1.19596 Z-0.20031
N0740 G04 X3.0
N0760 G01 X1.21244 Z-0.17204
N0765 G01 X1.78467 Z-0.26225
N0775 G01 X1.21244 Z-0.17204
N0790 G04 X3.0
N0810 G01 X1.23138 Z-0.14415
N0815 G01 X1.79519 Z-0.24676
N0825 G01 X1.23138 Z-0.14415
N0840 G04 X3.0
N0860 G01 X1.25273 Z-0.11670
N0865 G01 X1.80705 Z-0.23151
N0875 G01 X1.25273 Z-0.11670
N0890 G04 X3.0
N0910 G01 X1.27645 Z-0.08974
N0915 G01 X1.82023 Z-0.21653
N0925 G01 X1.27645 Z-0.08974
N0940 G04 X3.0
N0960 G01 X1.30250 Z-0.06333
N0965 G01 X1.83471 Z-0.20186
N0975 G01 X1.30250 Z-0.06333
N0990 G04 X3.0
N1010 G01 X1.33083 Z-0.03751
N1015 G01 X1.85045 Z-0.18751
N1025 G01 X1.33083 Z-0.03751
N1040 G04 X3.0
N1060 G01 X1.36139 Z-0.01233
N1065 G01 X1.86742 Z-0.17352
N1075 G01 X1.36139 Z-0.01233
N1090 G04 X3.0
N1110 G01 X1.39411 Z0.01216
N1115 G01 X1.88560 Z-0.15992
N1125 G01 X1.39411 Z0.01216
N1140 G04 X3.0
N1160 G01 X1.42894 Z0.03591
N1165 G01 X1.90495 Z-0.14672
N1175 G01 X1.42894 Z0.03591
N1190 G04 X3.0
N1210 G01 X1.46581 Z0.05887
N1215 G01 X1.92544 Z-0.13396
N1225 G01 X1.46581 Z0.05887
N1240 G04 X3.0
N1260 G01 X1.50465 Z0.08102
N1265 G01 X1.94701 Z-0.12166
N1275 G01 X1.50465 Z0.08102
N1290 G04 X3.0
N1310 G01 X1.54538 Z0.10229
N1315 G01 X1.96964 Z-0.10984
N1325 G01 X1.54538 Z0.10229
N1340 G04 X3.0
N1360 G01 X1.58793 Z0.12266
N1365 G01 X1.99328 Z-0.09853
N1375 G01 X1.58793 Z0.12266
N1390 G04 X3.0
N1410 G01 X1.63221 Z0.14208
N1415 G01 X2.01788 Z-0.08774
N1425 G01 X1.63221 Z0.14208
N1440 G04 X3.0
N1460 G01 X1.67815 Z0.16051
N1465 G01 X2.04340 Z-0.07750
N1475 G01 X1.67815 Z0.16051
N1490 G04 X3.0
N1510 G01 X1.72565 Z0.17792
N1515 G01 X2.06980 Z-0.06782
N1525 G01 X1.72565 Z0.17792
N1540 G04 X3.0
N1560 G01 X1.77462 Z0.19429
N1565 G01 X2.09700 Z-0.05873
N1575 G01 X1.77462 Z0.19429
N1590 G04 X3.0
N1610 G01 X1.82498 Z0.20956
N1615 G01 X2.12498 Z-0.05024
N1625 G01 X1.82498 Z0.20956
N1640 G04 X3.0
N1660 G01 X1.87662 Z0.22373
N1665 G01 X2.15367 Z-0.04237
N1675 G01 X1.87662 Z0.22373
N1690 G04 X3.0
N1710 G01 X1.92945 Z0.23676
N1715 G01 X2.18302 Z-0.03514
N1725 G01 X1.92945 Z0.23676
N1740 G04 X3.0
N1760 G01 X1.98336 Z0.24862
N1765 G01 X2.21297 Z-0.02855
N1775 G01 X1.98336 Z0.24862
N1790 G04 X3.0
N1810 G01 X2.03826 Z0.25929
```

```
N1815 G01 X2.24347 Z-0.02262
N1825 G01 X2.03826 Z0.25929
N1840 G04 X3.0
N1860 G01 X2.09404 Z0.26876
N1865 G01 X2.27446 Z-0.01736
N1875 G01 X2.09404 Z0.26876
N1890 G04 X3.0
N1910 G01 X2.15058 Z0.27700
N1915 G01 X2.30588 Z-0.01278
N1925 G01 X2.15058 Z0.27700
N1940 G04 X3.0
N1960 G01 X2.20780 Z0.28400
N1965 G01 X2.33766 Z-0.00889
N1975 G01 X2.20780 Z0.28400
N1990 G04 X3.0
N2010 G01 X2.26557 Z0.28975
N2015 G01 X2.36976 Z-0.00570
N2025 G01 X2.26557 Z0.28975
N2040 G04 X3.0
N2060 G01 X2.32378 Z0.29423
N2065 G01 X2.40210 Z-0.00321
N2075 G01 X2.32378 Z0.29423
N2090 G04 X3.0
N2110 G01 X2.38234 Z0.29743
N2115 G01 X2.43463 Z-0.00143
N2125 G01 X2.38234 Z0.29743
N2140 G04 X3.0
N2160 G01 X2.44111 Z0.29936
N2165 G01 X2.46728 Z-0.00036
N2175 G01 X2.44111 Z0.29936
N2190 G04 X3.0
N2210 G01 X2.50000 Z0.30000
N2215 G01 X2.50000 Z0.00000
N2225 G01 X2.50000 Z0.30000
N2240 G04 X3.0
N2260 G01 X2.55889 Z0.29936
N2265 G01 X2.53272 Z-0.00036
N2275 G01 X2.55889 Z0.29936
N2290 G04 X3.0
N2310 G01 X2.61766 Z0.29743
N2315 G01 X2.56537 Z-0.00143
N2325 G01 X2.61766 Z0.29743
N2340 G04 X3.0
N2360 G01 X2.67622 Z0.29423
N2365 G01 X2.59790 Z-0.00321
N2375 G01 X2.67622 Z0.29423
N2390 G04 X3.0
N2410 G01 X2.73443 Z0.28975
N2415 G01 X2.63024 Z-0.00570
N2425 G01 X2.73443 Z0.28975
N2440 G04 X3.0
N2460 G01 X2.79220 Z0.28400
N2465 G01 X2.66234 Z-0.00889
N2475 G01 X2.79220 Z0.28400
N2490 G04 X3.0
N2510 G01 X2.84942 Z0.27700
N2515 G01 X2.69412 Z-0.01278
N2525 G01 X2.84942 Z0.27700
N2540 G04 X3.0
N2560 G01 X2.90596 Z0.26876
N2565 G01 X2.72554 Z-0.01736
N2575 G01 X2.90596 Z0.26876
N2590 G04 X3.0
N2610 G01 X2.96174 Z0.25929
N2615 G01 X2.75653 Z-0.02262
N2625 G01 X2.96174 Z0.25929
N2640 G04 X3.0
N2660 G01 X3.01664 Z0.24862
N2665 G01 X2.78703 Z-0.02855
N2675 G01 X3.01664 Z0.24862
N2690 G04 X3.0
N2710 G01 X3.07055 Z0.23676
N2715 G01 X2.81698 Z-0.03514
N2725 G01 X3.07055 Z0.23676
N2740 G04 X3.0
N2760 G01 X3.12338 Z0.22373
N2765 G01 X2.84633 Z-0.04237
N2775 G01 X3.12338 Z0.22373
N2790 G04 X3.0
N2810 G01 X3.17502 Z0.20956
N2815 G01 X2.87502 Z-0.05024
N2825 G01 X3.17502 Z0.20956
N2840 G04 X3.0
N2860 G01 X3.22538 Z0.19429
N2865 G01 X2.90300 Z-0.05873
N2875 G01 X3.22538 Z0.19429
N2890 G04 X3.0
N2910 G01 X3.27435 Z0.17792
N2915 G01 X2.93020 Z-0.06782
N2925 G01 X3.27435 Z0.17792
N2940 G04 X3.0
N2960 G01 X3.32185 Z0.16051
N2965 G01 X2.95660 Z-0.07750
N2975 G01 X3.32185 Z0.16051
N2990 G04 X3.0
N3010 G01 X3.36779 Z0.14208
N3015 G01 X2.98212 Z-0.08774
N3025 G01 X3.36779 Z0.14208
N3040 G04 X3.0
N3060 G01 X3.41207 Z0.12266
N3065 G01 X3.00672 Z-0.09853
N3075 G01 X3.41207 Z0.12266
N3090 G04 X3.0
N3110 G01 X3.45462 Z0.10229
N3115 G01 X3.03036 Z-0.10984
N3125 G01 X3.45462 Z0.10229
N3140 G04 X3.0
N3160 G01 X3.49535 Z0.08102
```

```
N3165 G01 X3.05299 Z-0.12166
N3175 G01 X3.49535 Z0.08102
N3190 G04 X3.0
N3210 G01 X3.53419 Z0.05887
N3215 G01 X3.07456 Z-0.13396
N3225 G01 X3.53419 Z0.05887
N3240 G04 X3.0
N3260 G01 X3.57106 Z0.03591
N3265 G01 X3.09505 Z-0.14672
N3275 G01 X3.57106 Z0.03591
N3290 G04 X3.0
N3310 G01 X3.60589 Z0.01216
N3315 G01 X3.11440 Z-0.15992
N3325 G01 X3.60589 Z0.01216
N3340 G04 X3.0
N3360 G01 X3.63861 Z-0.01233
N3365 G01 X3.13258 Z-0.17352
N3375 G01 X3.63861 Z-0.01233
N3390 G04 X3.0
N3410 G01 X3.66917 Z-0.03751
N3415 G01 X3.14955 Z-0.18751
N3425 G01 X3.66917 Z-0.03751
N3440 G04 X3.0
N3460 G01 X3.69750 Z-0.06333
N3465 G01 X3.16529 Z-0.20186
N3475 G01 X3.69750 Z-0.06333
N3490 G04 X3.0
N3510 G01 X3.72355 Z-0.08974
N3515 G01 X3.17977 Z-0.21653
N3525 G01 X3.72355 Z-0.08974
N3540 G04 X3.0
N3560 G01 X3.74727 Z-0.11670
N3565 G01 X3.19295 Z-0.23151
N3575 G01 X3.74727 Z-0.11670
N3590 G04 X3.0
N3610 G01 X3.76862 Z-0.14415
N3615 G01 X3.20481 Z-0.24676
N3625 G01 X3.76862 Z-0.14415
N3640 G04 X3.0
N3660 G01 X3.78756 Z-0.17204
N3665 G01 X3.21533 Z-0.26225
N3675 G01 X3.78756 Z-0.17204
N3690 G04 X3.0
N3710 G01 X3.80404 Z-0.20031
N3715 G01 X3.22448 Z-0.27796
N3725 G01 X3.80404 Z-0.20031
N3740 G04 X3.0
N3760 G01 X3.81804 Z-0.22892
N3765 G01 X3.23226 Z-0.29385
N3775 G01 X3.81804 Z-0.22892
N3790 G04 X3.0
N3810 G01 X3.82953 Z-0.25780
N3815 G01 X3.23864 Z-0.30990
N3825 G01 X3.82953 Z-0.25780
N3840 G04 X3.0
N3860 G01 X3.83849 Z-0.28691
N3865 G01 X3.24362 Z-0.32607
N3875 G01 X3.83849 Z-0.28691
N3890 G04 X3.0
N3910 G01 X3.84490 Z-0.31619
N3915 G01 X3.24719 Z-0.34233
N3925 G01 X3.84490 Z-0.31619
N3940 G04 X3.0
N3960 G01 X3.84875 Z-0.34558
N3965 G01 X3.24933 Z-0.35866
N3975 G01 X3.84875 Z-0.34558
N3990 G04 X3.0
N4010 G01 X3.85004 Z-0.37502
N4015 G01 X3.25004 Z-0.37502
N4025 G01 X3.85004 Z-0.37502
N4040 G04 X3.0
N4060 G01 X3.84875 Z-0.40446
N4065 G01 X3.24933 Z-0.39138
N4075 G01 X3.84875 Z-0.40446
N4090 G04 X3.0
N4110 G01 X3.84490 Z-0.43385
N4115 G01 X3.24719 Z-0.40771
N4125 G01 X3.84490 Z-0.43385
N4140 G04 X3.0
N4160 G01 X3.83849 Z-0.46313
N4165 G01 X3.24362 Z-0.42397
N4175 G01 X3.83849 Z-0.46313
N4190 G04 X3.0
N4210 G01 X3.82953 Z-0.49224
N4215 G01 X3.23864 Z-0.44014
N4225 G01 X3.82953 Z-0.49224
N4240 G04 X3.0
N4265 G00 X30.4 Z13.0 T00 ! BACK TO REF COORDS, CLEAR TOOL
N4270 G92 X0 Z(P43)       ! BACK TO PROBING START
N4275 G00 Z10             ! BACK TO INITIAL MACHINE POSITION
N4280 M30                 ! REWIND Program
N9999 (END, PROG)
```

A2. NC Program to Measure the 2-in Gauge Block

This NC program was used for obtaining the data for measurement of the 2 in standard bar in machine space. Touches were made on both ends of the bar and the (X,Z) location of the probe on the machine was captured by the RTEC unit and recorded by the computer.

```
N0010 (ID,PROG,999022,Bar PROBING)
N0020 ! Fri Mar 19, 1999
N0030 ! Tool 5:  Touch-trigger probe w/ext. in 7.1" boring bar holder.
N0040 !   Length: Z=-10.7765 X=-7.9855 Offset 5: Z=-0.0200 X=0.100
N0050 ! Touch face of part, then MDI W2.2235 for PROBING START
N0060 ! P43 = PROBING START: Machine Z coordinate to which
N0080 !   Home [X0, Z10].
N0090 ! Probe tip diameter = 0.197"
N0100 ! Feedrate = 100 (inches per minute)
N0110 ! Touch face at part zero is on dome surface, Z-axis.
N0120 ! Program probes alternate pts on top and bottom bar
N0130 G70       ! INCH MODE
N0140 T0500         ! INDEX TURRET TO PROBE
N0150 G94 T00           ! INCHES/MIN, CLEAR TOOL
N0160 G00 Z(P43)        ! RAPID TO PROBING START
N0170 G92 X30.4 Z13.0    ! PRESET REF COORDS
N0180 M14               ! TURN ON PROBE
N0190 M15       !
N0200 G00 X10.6 Z-0.2 T0505 ! Go to first point
N2490 G00 X10.6 Z-0.2
N2495 G01 X10.0 Z-0.2 F100 ! Touch
N2500 G01 X10.6 Z-0.2  ! Retract
N2502 G00 X10.6 Z0.3
N2504 G00 X5.4 Z0.3
N2506 G00 X5.4 Z-0.2
N2508 G01 X6.0 Z-0.2  ! Touch
N2510 G01 X5.4 Z-0.2  ! Retract
N2512 G00 X5.4 Z0.3
N2514 G00 X10.4 Z0.3
N2505 G04 X0.25
/N2510 (GOTO N2645)
N2515 (GOTO N2490)
N2645 G00 X30.4 Z13.0 T00 ! BACK TO REF COORDS, CLEAR TOOL
N2650 G92 X0 Z(P43)      ! BACK TO PROBING START
N2655 G00 Z10           ! BACK TO INITIAL MACHINE POSITION
N2660 M30               ! REWIND Program
N9999 (END, PROG)
```

Appendix B. C program used to generate the NC program listed in Appendix A.

This program reads the matlab file and generates the NC program, minus the 'boiler plate' at the beginning and end of the program.

```
/* nc_probe.c                                              */
/*                                                         */
/* Program reads input point files to write NC program    */
/* ...Monarch Metalist probing on standard sphere.        */
/* The point file was generated using MatLab and each     */
/* ...line contains the x0, y0, xR, yR values.            */
/* Written by Neil D. Wilkin 3/11/99                      */

#include <stdio.h>


void main(int argc, char *argv[])
    {
    FILE *fptr;
    FILE *fptr1;
    FILE *fptw;
    int i;
    int count = 210;
    char lines[81];
    float offset = 1.25;
    char ch;
    float x0, y0, xR, yR;

    if((fptr=fopen("monarch.txt", "r")) == NULL)  /*   open read file   */
            {
            printf("Can't open monarch.txt file %s\n");
            exit();
            }

    if((fptr1=fopen("boiler1.dnc", "r")) == NULL)  /*   open read file   */
            {
            printf("Can't open boiler1.dnc file\n");
            exit();
            }

    if((fptw=fopen("PT999022.DNC", "w")) == NULL)  /*   open write file   */
            {
            printf("Can't open write file %s\n", "PTSPHERE.DNC");
            exit();
            }

    while((fgets(lines,80,fptr1) != NULL) || (kbhit())) /*get string*/
            {
            //printf("%s", &lines);
            fputs(lines,fptw);
            }

    //getch();
```

```
while(fscanf(fptr, "%f, %f, %f, %f", &x0, &y0, &xR, &yR) != EOF) /*get string*/
        {
        //printf("%.5f %.5f %.5f %.5f\n", x0, y0, xR, yR);
        fprintf(fptw,"N%04d G01 X%.5f Z%.5f\n", count, (2 * (yR + offset)), xR);
        count += 5;
        fprintf(fptw,"N%04d G01 X%.5f Z%.5f\n", count, (2 * (y0 + offset)), x0);
        count += 10;
        fprintf(fptw,"N%04d G01 X%.5f Z%.5f\n", count, (2 * (yR + offset)), xR);
        count += 15;
        fprintf(fptw,"N%04d G04 X3.0\n", count);
        count += 20;
        if (kbhit())
          {
          exit();
          }
        }
        fprintf(fptw,"N%04d G00 X30.4 Z13.0 T00 ! BACK TO REF COORDS, CLEAR
                TOOL\n", count+5);
        fprintf(fptw,"N%04d G92 X0 Z(P43)       ! BACK TO PROBING START\n",
                count+10);
        fprintf(fptw,"N%04d G00 Z10             ! BACK TO INITIAL MACHINE
                POSITION\n", count+15);
        fprintf(fptw,"N%04d M30               ! REWIND Program\n", count+20);
        fprintf(fptw,"N9999 (END, PROG)\n");
        fclose(fptr);
        fclose(fptr1);
        fclose(fptw);
        //fclose(
}
```

The following is the matlab generated data points, (generated in inches since the Monarch is programmed in Inches) (x0,y0) are the touch points and (xR,yR) are the approach points:

```
    x0          y0          xR          yR
-0.440141, -0.369322, -0.492236, -0.664765
-0.423970, -0.371811, -0.463127, -0.669245
-0.407705, -0.373593, -0.433852, -0.672451
-0.391378, -0.374663, -0.404464, -0.674377
-0.375020, -0.375020, -0.375020, -0.675020
-0.358662, -0.374663, -0.345576, -0.674377
-0.342335, -0.373593, -0.316188, -0.672451
-0.326070, -0.371811, -0.286912, -0.669245
-0.309898, -0.369322, -0.257804, -0.664765
-0.293851, -0.366130, -0.228919, -0.659019
-0.277957, -0.362241, -0.200312, -0.652019
-0.262249, -0.357663, -0.172037, -0.643778
-0.246755, -0.352403, -0.144149, -0.634311
-0.231506, -0.346473, -0.116701, -0.623637
-0.216530, -0.339883, -0.089744, -0.611776
-0.201855, -0.332647, -0.063330, -0.598750
-0.187510, -0.324777, -0.037510, -0.584584
-0.173522, -0.316288, -0.012332, -0.569306
-0.159917, -0.307198, 0.012156, -0.552944
```

-0.146722, -0.297523, 0.035906, -0.535529
-0.133962, -0.287282, 0.058875, -0.517095
-0.121660, -0.276494, 0.081017, -0.497677
-0.109841, -0.265179, 0.102291, -0.477311
-0.098526, -0.253360, 0.122657, -0.456037
-0.087738, -0.241058, 0.142075, -0.433894
-0.077497, -0.228298, 0.160509, -0.410926
-0.067822, -0.215102, 0.177924, -0.387175
-0.058731, -0.201498, 0.194286, -0.362688
-0.050243, -0.187510, 0.209565, -0.337510
-0.042373, -0.173165, 0.223730, -0.311689
-0.035136, -0.158490, 0.236756, -0.285276
-0.028547, -0.143514, 0.248617, -0.258319
-0.022616, -0.128264, 0.259291, -0.230870
-0.017357, -0.112771, 0.268758, -0.202982
-0.012778, -0.097062, 0.276999, -0.174708
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